EA417F
Flight Test IB

Power Required

I. *Purpose*

To determine the level flight unaccelerated power required as a function of flight speed, and in conjunction with data on engine power and propeller efficiency to estimate various aircraft performance parameters.

II. *References*

1. Hurt, "Aerodynamics for Naval Aviators," pp. 95-106, 135-158.
2. Anderson, J. D., "Introduction to Flight", Chapter 6.
3. Anderson, J. D., "Aircraft Performance and design", Chapter 5.
4. http://web.usna.navy.mil/~dfr/technical_flying.html
5. Class notes

III. *Background and Theory*

Drag

Drag is composed of three principal elements. One is due to the resultant of the pressure forces acting on the body when the flow separates and forms a wake behind the body. This drag is called *form drag*, or sometimes *pressure drag.* The second element is *skin friction drag*, or *viscous drag*, and results from the shearing stresses that occur when a fluid flows over the body surface. Most bodies are subject to both skin friction and form drag. The total body drag, including both types of drag, is usually referred to as *parasite* drag.

The third element of drag is associated with lift on a lifting surface, e.g., a wing. The lower pressure on top of a wing induces a flow around the wingtips from the higher pressure air below the wing. Because the wing is moving forward, this circular motion of air trails behind each wingtip and is referred to as a trailing (or wing tip) vortex. The trailing vortices induce a downward flow behind the wing called the downwash field. Consequently, the streamwise flow, originally in the free stream direction of V_∞, is deflected downward. Because lift is defined as the force created perpendicular to the free stream direction and drag parallel to the free stream direction, the component of the resultant force parallel to the free stream direction, i.e., the drag, is increased. This additional drag is called *induced drag.* Thus, for a wing, the total drag becomes

$$D = D_p + D_i \tag{1-1}$$

where

$$D_p = \text{parasite drag}$$
$$D_i = \text{induced drag}$$

In coefficient form, we have

$$C_D = C_{D_p} + C_{D_i} \tag{1-2}$$

It can be shown that for an elliptical wing, the induced drag coefficient is defined in terms of the lift coefficient and aspect ratio as

$$C_{D_i} = \frac{C_L^2}{\pi \mathrm{AR}} \tag{1-3}$$

where

$$\mathrm{AR} = \frac{b^2}{\mathrm{S}}$$
$$b = \text{wing span}$$
$$\mathrm{S} = \text{wing area}$$

This result is rather intuitive, because the induced drag resulting from lift should be proportional to some function of the lift. It is also intuitive that a higher aspect ratio wing which places the trailing vortices a greater distance apart should tend to induce less deflection of the resultant force vector and thus cause less induced drag.

In dealing with an entire aircraft, a number of different parts of the aircraft contribute to the parasite drag. The fuselage, the wing, the nacelles, the tail and all the other various parts each create parasite drag. The wing, on the other hand, is the only significant creator of induced drag. It is therefore customary, in making an estimation of aircraft drag, to compute the total parasite drag by summing the drag of the various components. The induced drag is dealt with separately.

Drag Buildup

Estimating the total parasite drag by considering the drag of each component is commonly referred to as a drag buildup. Drag coefficients and related areas are determined for each component. A drag coefficient is defined as

$$C_D = \frac{\text{drag}}{q\,(\text{area})} \tag{1 – 4}$$

The drag is the streamwise component of force measured, for example, on a force balance, and q is the dynamic pressure. Because bodies are three-dimensional, the reference area is somewhat arbitrary. For example, the body in Figure 2–1 has a projected frontal area of two square feet, a planform area of five square feet, and a side-view area of four square feet. If q is equal to one pound per square foot and a drag force of 2 lbs is exerted, based on the frontal area the C_D is 1.0, based on the planform area the C_D is 0.4 and based on the side-view area the C_D is O.5. Notice that the choice of reference area has a great effect on the value of the drag coefficient. However, the product of the drag coefficient and the area is the same in all cases.

The drag coefficient for parasite drag of an aircraft component is referred to as a *proper drag coefficient*, C_{D_π}; and the area on which it is based is called the *proper area*, A_π. Normally, for bluff bodies, or bodies of appreciable thickness, such as a fuselage, nacelle or external fuel tank, the proper area is taken as the projected

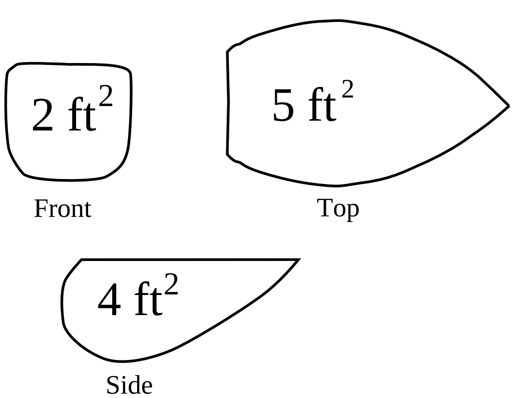

Figure 2–1 Proper areas for bodies.

frontal area. For bodies with a mostly flat surface area, such as wings or tail surfaces, the planform area is usually considered the proper area. The product of the proper area and proper drag coefficient is called the equivalent parasite area, or equivalent flat plate area f. This serves to express the drag in terms of the area of an equivalent flat plate with a drag coefficient of 1.0. Thus, the equivalent flat plate area is

$$f = C_{D_\pi} A_\pi \tag{1-5}$$

The drag breakdown, then, consists of tabulating the C_{D_π} and A_π values for various components of the aircraft, calculating the equivalent flat plate area, f, for each component and summing them to give a total f for the overall aircraft. Values of C_{D_π} must be chosen by referring to empirical data for configurations similar to that for which the drag is being estimated. Care must be taken in selecting values in the proper range of Reynolds number, and also in making sure of the proper area on which the C_{D_π} is based.

When two bodies are brought into close proximity or joined, the total drag is more than the sum of the drag on the two bodies individually. The additional drag that results in such cases is called *interference drag*. Interference drag is extremely difficult to estimate. Thus, an additional 5 to 10% of the total f is added to the estimated drag to account for the effects of interference drag. An additional 5 to 10% should also be allowed for protuberances such as antennas, lights, radomes and the like. Listed below is a typical drag breakdown.

Component	C_{D_π}	$A_\pi(\mathrm{ft}^2)$	$f(\mathrm{ft}^2)$
Wing	.007	192	1.344
Fuselage	.12	20	2.400
Horizontal tail	.006	33	.198
Vertical tail	.006	16	.096
			4.038
10% interference and protuberance			.404
			4.442

The total parasite drag coefficient for the aircraft is normally based on the wing planform area, S. Thus, the parasite drag coefficient, C_{D_p}, for the aircraft can be determined from the total equivalent flat plate area

$$C_{D_p} = \frac{f}{\mathrm{S}} \tag{1-6}$$

Airplane Efficiency Factor

For wings with other than elliptical, but near elliptical planform, the induced drag is slightly higher. Corrections for nonelliptical wing planform are available, e.g., the Glauert factor $(1+\delta)$ which is a function of taper ratio. Furthermore, the parasite drag coefficient is really a minimum drag coefficient as estimated, because it assumes all components are aligned at the optimum angle to the airstream. With changes in pitch attitude of the aircraft, which occur with angle of attack changes, the C_{D_p} of the aircraft changes slightly. Thus, the assumption that the parasite drag coefficient is constant for all C_L values is not quite correct. The total drag coefficient is more correctly described as

$$C_D = C_{D_{p\,\mathrm{min}}} + K C_L^2 + (1+\delta)\frac{C_L^2}{\pi \mathrm{AR}} \tag{1-7}$$

K is some factor which accounts for the increase in parasite drag over the minimum value with change in aircraft attitude, and $(1+\delta)$ is the Glauert nonelliptical wing correction factor. Because both of these factors are functions of C_L^2, it is customary to account for both of them in the induced drag term by a factor e. This term is called the *Oswald efficiency factor*, or aircraft efficiency factor. The final drag equation, in coefficient form, then becomes

$$C_D = C_{D_{p\,\min}} + \frac{C_L^2}{\pi \mathrm{AR} e} \qquad (1-8)$$

The value e can be estimated for a particular model of aircraft by various methods. One of the simplest is by comparison with aircraft of similar configuration. For most aircraft e has a value of about 0.6 to 0.8. Some values of e for various aircraft as measured at Mississippi State University are

Bellancer Crusair (low-wing)	0.55
Learstar (twin engine mid-wing)	0.67
Cessna 170 (high-wing)	0.74
RJ-5 Glider (high-wing)	0.79

Total Drag

The total drag of the aircraft is defined as the total drag coefficient multiplied by the dynamic pressure and the wing planform area. Thus

$$D = C_D \frac{1}{2}\rho V^2 \mathrm{S} = \left(C_{D_p} + \frac{C_L^2}{\pi \mathrm{AR} e}\right)\frac{1}{2}\rho V^2 \mathrm{S} \qquad (1-9)$$

Multiplying through yields

$$D = \frac{C_{D_p}\mathrm{S}\rho V^2}{2} + \frac{C_L^2 \mathrm{S}\rho V^2}{2\pi \mathrm{AR} e} \qquad (1-10)$$

Noting that the quantity $C_{D_p}\mathrm{S}$ in the first term is equal to the equivalent flat plate area, f, and recalling that

$$C_L = \frac{W}{{}^1\!/\!_2\,\rho V^2 \mathrm{S}} \qquad (1-11)$$

$$\mathrm{AR} = \frac{b^2}{\mathrm{S}}$$

and substituting, the drag equation is rewritten as

$$D = f\frac{\rho}{2}V^2 + \frac{2}{\rho\pi e}\left(\frac{W}{b}\right)^2\frac{1}{V^2} \qquad (1-12)$$

The first term in this equation is the parasite drag and, for a given dynamic pressure, is seen to depend entirely on f. The second term represents the induced drag; it is proportional to the square of the ratio W/b, sometimes called the span loading. Note that parasite drag is directly proportional to the square of velocity, while induced drag is inversely proportional to the square of the velocity. Figure 2–2 shows a plot of parasite, induced and total drag as functions of velocity. The fact that drag rises from some minimum point with both increase and decrease in velocity is of tremendous importance in the performance of an aircraft.

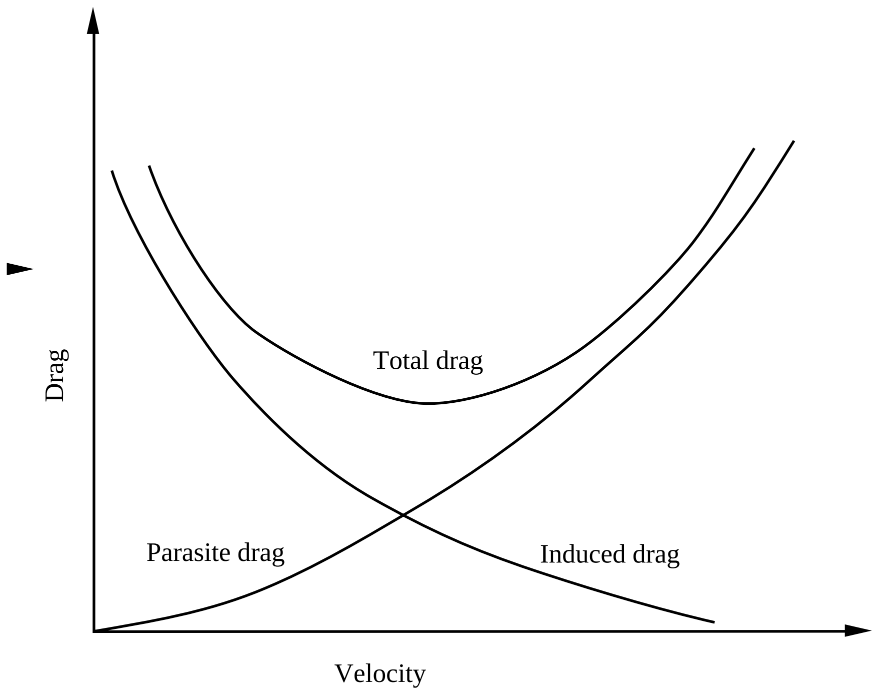

Figure 2–2 Typical drag curves.

Power Required

Because in steady level flight drag represents the force which must be overcome by the thrust of the engine, the drag curve is sometimes referred to as the thrust required curve. For comparison, the maximum thrust output of the engine is frequently plotted on the same graph. This curve is referred to as the thrust available. These quantities are normally used in just that way for a jet engine where the output is measured in pounds of thrust. However, for a propeller-driven aircraft, the engine's useful output is more easily determined in terms of horsepower. Therefore, the normal procedure with propeller-driven aircraft is to plot power available against power required.

Power is defined as force times velocity. Thus, multiplying the drag or thrust required equation by velocity yields an expression for power required

$$P = DV = f\frac{\rho}{2}V^3 + \frac{2}{\rho\pi e}\left(\frac{W}{b}\right)^2\frac{1}{V} \qquad (1-13)$$

A typical power required curve is shown in Figure 2–3.

Power Available

The power required curve represents the power that must be produced by the engine to maintain steady level flight. Thus, in steady level flight the power required at any flight speed is determined by measuring the power output of the engine.

A reciprocating engine develops a certain amount of power at its shaft depending on the RPM, manifold pressure and atmospheric density. Power charts, typically furnished by the manufacturer, give the brake horsepower for a given set of conditions. The power indicated by this chart is that available at the output shaft of the engine and is called brake horsepower (BHP). Power, however, must be converted into useful thrust by some mechanical means. In this case, the propeller is the converting

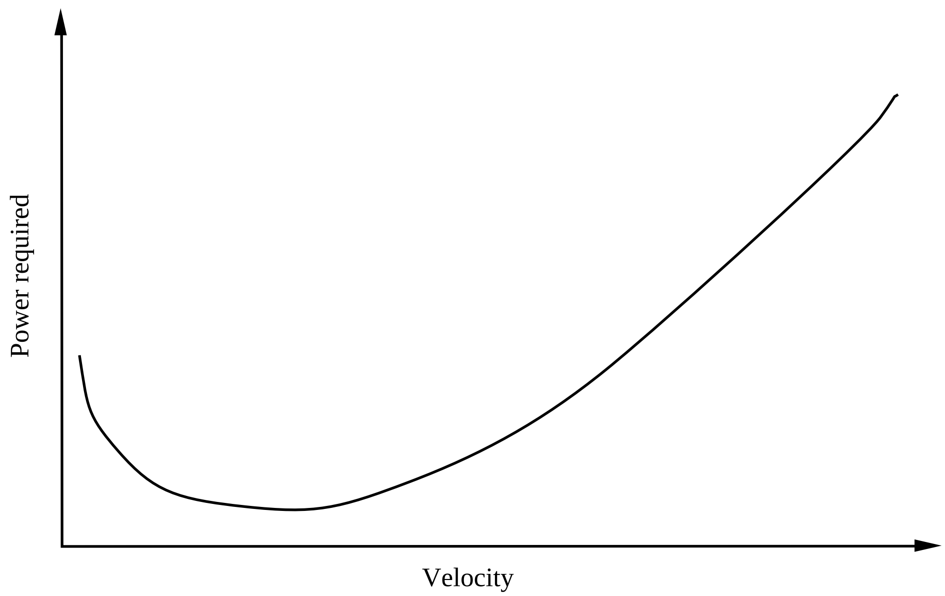

Figure 2–3 Power required vs velocity.

mechanism. As with all mechanical devices, some power is lost in the conversion depending on the efficiency of the process employed. The resulting useful thrust is called thrust horsepower. In steady level flight this is the power required. Thrust horsepower is related to brake horsepower through the propeller efficiency, η_p. Thus, thrust horsepower is

$$\text{THP} = \eta_p \text{BHP} \tag{1 - 14}$$

Propeller Efficiency

A propeller blade is really a small wing rotating in a vertical plane so that its 'lift' vector is directed generally forward, thus producing thrust. Because the propeller blade is also moving forward as it rotates, the resultant velocity meets the blade at some angle much smaller than its geometric pitch (see Figure 2–4). The blade performs at maximum efficiency at some specified value of this angle-of-attack corresponding to an angle for maximum L/D. Varying either the forward or rotational velocity changes this angle-of-attack and thus changes the efficiency. Consequently, the efficiency is dependent on the ratio of forward to rotational velocity. This nondimensional ratio is termed the advance ratio, J, where

$$J = \frac{V}{nD}$$

where $V =$ forward velocity

$n =$ rotational velocity

$D =$ propeller diameter

A typical propeller efficiency chart is shown in Figure 2–5. Various curves are shown for various values of pitch angle β. A fixed pitch propeller will perform according to the curve for its particular pitch. Some aircraft, however, have propellers equipped with a mechanism to vary the pitch in flight. Thus, the maximum efficiency can be obtained over a wider range of J values. Propeller efficiency curves are

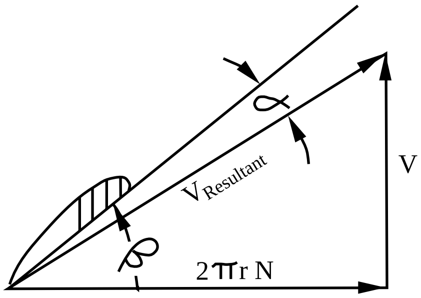

Figure 2–4 Propeller section.

determined experimentally by measuring the power and thrust for various values of J. Thrust T and power P are usually expressed in coefficient form as C_T and C_p, respectively

$$C_{\mathrm{T}} = \frac{\mathrm{T}}{\rho n^2 D^4}$$

$$C_{\mathrm{P}} = \frac{\mathrm{P}}{\rho n^3 D^5}$$

The efficiency, in terms of these coefficients, is then

$$\eta_p = \frac{C_{\mathrm{T}}}{C_{\mathrm{P}}} J$$

Generalized Power Curves

In order to standardize performance data, it is necessary to reduce all data to standard weight and standard sea level conditions. If we define CAS_W as calibrated airspeed corrected to standard weight, and THP_{ew} as thrust horsepower required at standard weight at sea level, where the subscript ew stands for equivalent weight, then

$$\mathrm{CAS}_W = \sqrt{\frac{2W_{\mathrm{S}}}{\rho_{\mathrm{SL}} C_L \mathrm{S}}} \qquad (1-15)$$

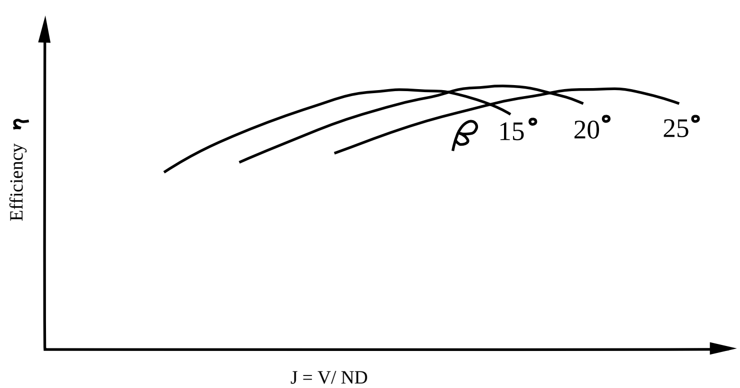

Figure 2–5 Propeller efficiency.

$$\mathrm{THP}_{ew} = \frac{1}{550}\sqrt{\frac{2W_{\mathrm{S}}^3 C_D^2}{\rho_{\mathrm{SL}}\mathrm{S}\,C_L^3}} \qquad (1-16)$$

where W_{S} = standard weight and 550 is the conversion from ft lbs/sec to horsepower.

The airspeed and power under any other set of conditions are,

$$\mathrm{CAS} = \sqrt{\frac{2W}{\rho_{\mathrm{SL}}\,C_L\mathrm{S}}} \qquad (1-17)$$

$$\mathrm{THP} = \frac{1}{550}\sqrt{\frac{2W^3 C_D^2}{\rho\mathrm{S}\,C_L^3}} \qquad (1-18)$$

where $\mathrm{TAS} = \mathrm{CAS}/\sqrt{\sigma}$, $\sigma = \rho/\rho_{\mathrm{SL}}$, W and ρ are the actual weight and density for the particular conditions. Note, calibrated and equivalent airspeed are assumed identical for low altitudes.

Thus, at the same C_L, the equivalent weight airspeed is related to actual airspeed, and equivalent weight power is related to actual power by

$$\mathrm{CAS}_W = \mathrm{CAS}\left(\frac{W_{\mathrm{S}}}{W}\right)^{1/2} \qquad (1-19)$$

$$\mathrm{THP}_{ew} = \mathrm{THP}\sqrt{\sigma}\left(\frac{W_{\mathrm{S}}}{W}\right)^{3/2} \qquad (1-20)$$

and $\mathrm{TAS}_W = \mathrm{CAS}_W/\sqrt{\sigma}$.

Data taken at any measured airspeed and power is reduced to a standard weight and sea level conditions through use of these relationships. Standard weight is any reference weight of significance to performance. It is usually considered as the maximum certificated gross weight.

Determining e and f Experimentally

The generalized equations for airspeed and power are utilized to determine experimentally the value of aircraft efficiency factor and the equivalent flat plate area. For this purpose it is necessary to plot $\mathrm{THP}_{ew}(\mathrm{CAS}_W)$ as a function of CAS_W^4. Referring to Eq. $(1-13)$, the equation for power required is

$$\mathrm{THP} = A\sigma f V^3 + B\frac{1}{\sigma e}\left(\frac{W}{b}\right)^2\frac{1}{V} \qquad (1-21)$$

where $A = \rho_{\mathrm{SL}}/(2(550))$ and $B = 2/(\pi\rho_{\mathrm{SL}}550)$ are constants and V represents true airspeed TAS. Using Eqs. $(1-19$ and $1-20)$ we have

$$\mathrm{THP}_{ew}\mathrm{CAS}_W = \mathrm{THP}\left[\sqrt{\sigma}\left(\frac{W_{\mathrm{S}}}{W}\right)^{3/2}\right]\left[\mathrm{CAS}\left(\frac{W_{\mathrm{S}}}{W}\right)^{1/2}\right] \qquad (1-22)$$

and substituting Eq. $(1-21)$ into Eq. $(1-22)$ and reducing yields

$$\mathrm{THP}_{ew}\mathrm{CAS}_W = Af\,\mathrm{CAS}_W^4 + B\frac{1}{e}\left(\frac{W_{\mathrm{S}}}{b}\right)^2 \qquad (1-23)$$

Note that the equation is independent of density or actual weight and is linear in terms of CAS_W^4. Thus, a plot of $\mathrm{THP}_{ew}\mathrm{CAS}_W$ as a function of CAS_W^4 from experimental data should yield a straight line with a slope of Af and an intercept equal to $B/e\left(W_S/b^2\right)$. For power in horsepower and airspeed in feet-per-second, the constants A and B become 2.16×10^{-6} and 0.486, respectively. Because W_S/b is a constant for a given aircraft, the quantities f and e are determined by

$$f = \frac{\text{(slope of the straight line)}}{2.16 \times 10^{-6}}$$

$$e = \frac{0.486}{\text{(intercept with the ordinate)}}\left(\frac{W_S}{b}\right)^2$$

IV. *Procedure*

Stabilize the aircraft in level flight at the test altitude. Establish various power settings by choosing various RPM, MAP and fuel flow settings corresponding approximately to maximum BMEP.

Students shall:

1. Prior to flight, record aircraft tachometer reading and fuel quantity.
2. Determine aircraft weight.
3. Insure that 29.92 in Hg is set in the Kohlsman window of the altimeter.
4. During each run record IAS, MAP, RPM, OAT, altitude, fuel flow, fuel quantity and tachometer time.
5. Record postflight aircraft tachometer time.

V. *Flight test report requirements*

Determine standard day sea level brake horsepower and thrust horsepower available from aircraft engine performance charts and the propeller efficiency curve.

Plot:

a. $\mathrm{THP}_{ew_{\text{required}}}$ and $\mathrm{THP}_{\text{available}}$ as functions of CAS_W (kts).

b. T_{required} (or drag) and $T_{\text{available}}$ as functions of CAS_W (kts).

c. $\mathrm{THP}_{ew}\mathrm{CAS}_W$ as a function of CAS_W^4. (THP in horsepower; airspeed in ft/sec).

Determine the following performance parameters:

a. V_{maximum} at sea level (kts).

b. Sea level maximum range airspeed (kts).

c. Sea level maximum endurance airspeed (kts).

d. Speed for sea level maximum rate of climb (kts).

e. Sea level maximum rate of climb (fpm).

f. Speed for sea level maximum angle of climb (kts).

g. Maximum angle of climb at sea level (deg).

h. Airspeed for maximum range glide, power off.

c. Maximum power-off glide ratio.
d. Equivalent flat plate area (ft^2).
e. Airplane efficiency factor.

Include a set of detailed sample calculations for one power setting. Use any run you desire. For purposes of determining aircraft weight from the fuel quantity given by the fuel computer, average the weight at the beginning and the end of the run.